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30 Years of Optical Coherence Tomography: introduction to the feature issue

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Abstract: The guest editors introduce a feature issue commemorating the 30th anniversary of Optical Coherence Tomography.

This feature issue commemorates the more than 30-year history of Optical Coherence Tomography (OCT), one of the most successful biophotonic technologies. It continues a series of feature issues in *Biomedical Optics Express* that started with the 25-year anniversary issue that had been a great success in numbers of invited and contributed research papers [1]. Even though 5 years since then seem short, the readers may convince themselves by delving into the many contributed papers about the exciting developments in this fast and dynamic field of Biophotonics that easily justify such short update time.

The feature issue comprises 3 invited and 34 contributed research papers that are an impressive demonstration of the lasting innovative power of OCT even after three decades. As is well known, the term OCT has been coined in 1991 [2], with the technology being based on developments in low coherence interferometry and its application in biomedicine already in the 1980's. An important step stone in OCT development was the recognition and experimental demonstration of the sensitivity advantage of Fourier domain OCT [3–5] that paved the way of modern OCT technologies and in particular of fast functional OCT modalities such as OCT angiography or OCT elastography. Enabling high acquisition speed has been equally essential for the impressive developments in intraoperative OCT as well as endoscopic and catheter-based OCT. Parallel OCT modalities such as full field or line field OCT on the other hand score with high structural image fidelity and low motion distortion. All these aspects are well represented in this feature issue as will be detailed in due course.

We start with the invited review paper highlights a novel emerging technology being dynamic contrast OCT, with the promise to provide metabolic tissue information on the cellular level [6]. Contributed research papers demonstrate applications of dynamic OCT providing insight into activity of alveolar organoids [7] and improvement in dynamic OCT contrast such as by self-referencing and suppression of reflection artifacts in cell cultures [8]. OCT angiography (OCTA) has been the most successful functional extension of OCT that has been quickly translated to the ophthalmic clinics. An invited research paper, that has also been selected as editors pick, shows repeatable quantitative and temporally resolved blood flow analysis in the human retina across different capillary plexuses using variable interscan delay times [9]. Variable interscan

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times have also been realized using flexible scan patterns for quantitative OCTA as shown in [10]. A further contributed research paper deals with the improvement of OCTA image quality and the suppression of shadow artifacts [11], a fourth paper on OCTA shows a fast imaging pipeline for application in dermatology [12]. Another emerging field is intraoperative OCT, represented by two contributed research papers. One of them has been selected as editors pick visualizing surgical maneuvers with real time volumetric OCT [13], the second paper outlines methods for real-time feature-guided image fusion [14]. A functional extension in OCT with great promise is OCT elastography (OCE) represented by contributed papers showing compressed OCE for breast cancer tissue analysis [15], the assessment of corneal collagen cross linking by reconstruction of the depth resolved shear moduli [16], and the assessment of friction using micro-elastography [17]. Polarization sensitive OCT (PSOCT) is known to provide insight into tissue microstructure; one research papers discusses the application of PSOCT to the safety assessment of non-steroidal topical creams for dermatitis [18], a generalization termed Mueller matrix OCT analyses the organ development in zebrafish supported by deep learning [19]. On the technology side, linefield and full field OCT are attractive candidates for high speed or low-cost OCT in a most compact way without the need of complex light source technology or expensive data acquisition hardware. One paper demonstrates high parallelization, coined hyperparallel OCT, imaging of the anterior and posterior human eye [20], another paper demonstrates smartphone-based OCT using a linefield configuration [21]. Efficient line field illumination is demonstrated using a Powell lens [22], with another paper addressing reduction of spectral cross talk at the detector plane in linefield OCT and chromatic aberrations correction digitally [23]. Rapid full field optical coherence microscopy has been achieved using a ferroelectric liquid crystal element for geometric phase shifting [24]. Staying with full field OCT, a comparative analysis with optical transmission tomography has been presented in [25]. Instead of applying multiple image points as in parallel OCT a research paper discusses also the possibility to illuminate the sample through multiple apertures, that help in improving resolution, penetration, as well as reduce speckle noise [26]. Speckle noise from the epithelium might for example be a confounding factor in the quantitative analysis of corneal density based on OCT [27]. Visible light OCT is another technology with increasing interest. Apart from the beforementioned smartphone OCT, there are further two papers dedicated to this technology: one dealing with the application to dermatology [28], the second discusses the use of a narrow band light source in the visible range together with digital resolution enhancement [29]. Resolution enhancement using a generative adversarial network is the subject of another contributed paper to the feature issue [30]. As is well known, the OCT signal is generated through light scattering in tissue. However, multiple scattering is detrimental for image contrast. A paper that has been selected as editors pick, introduces a mapping of optical scattering properties into singly and multiply scattering samples [31] thereby exploiting the information contained even in multiple scattered light. Suppression of multiple scattering is shown by multi-focus averaging in [32]. Another theoretical analysis shows the possibility to introduce differential phase contrast digitally in enface OCT [33]. The feature issue also includes papers on biomedical applications of OCT to observe mouse ovarian follicles [34], to assess the human fallopian tube using a small OCT catheter [34], studying uveitis mouse models with deep learning assistance [35], providing real time feedback during laser osteotomy [36], and to image the correct anatomy of the middle ear in real time [37], and to predict the onset of atrophy in age-related macula degeneration patients using deep survival modeling [38]. Motion artifacts are often critical during in-vivo imaging, and methods to reduce those artifacts by efficient tracking are needed. A paper discusses high-dynamic motion tracking by applying circular scans with OCT [39]. A flexible scanner to cover the full eye is the subject of another contributed paper [40]. Clearly, medical application of OCT calls for phantoms that help to benchmark clinical OCT systems for various disease cases. A paper introduces a durable glaucoma phantom using ex-vivo mouse retinal tissue [41]. Finally, a research paper discusses how to improve the annotation task

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though self-supervised generative learning [42]. Annotation is a cumbersome and often manual effort, that is critical for machine learning assisted tissue segmentation tasks. As well visible from the various contributions to this feature issue, machine learning using deep neural networks has found entrance into various applications of OCT, ranging from image quality enhancement, noise reduction, resolution enhancement, segmentation, to disease prediction. It is a powerful tool with expectedly great impact on future developments in OCT as in other medical imaging technologies.

The Guest Editors wish to extend their sincere thanks to all of the authors, and the numerous anonymous reviewers, who contributed to this edition marking another installment in a series of OCT anniversary feature issues. We are particularly indebted to the authors of all of the Invited articles who agreed to take on and have fulfilled this challenging endeavour. Additionally, the Editors extend their thanks to the dedicated OPTICA staff, whose consistent professionalism and patient support were instrumental in this undertaking. We anticipate as for previous feature issues on OCT that the contents of this Issue will stand as an authoritative source on the current state of this exciting field, and look forward to many future anniversaries of OCT's contributions optics, science, and medicine.

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References

1. J. A. Izatt, S. A. Boppart, and B. Bouma, *et al.*, "Introduction to the feature issue on the 25 year anniversary of optical coherence tomography," Biomed. Opt. Express **8**(7), 3289–3291 (2017).
2. D. Huang, E. A. Swanson, and C. P. Lin, *et al.*, "Optical Coherence Tomography," Science **254**(5035), 1178–1181 (1991).
3. R. Leitgeb, C.K. Hitzenberger, and A.F. Fercher, "Performance of Fourier domain vs. time domain optical coherence tomography," Opt. Express **11**(8), 889–894 (2003).
4. J.F. De Boer, B. Cense, and B. Hyle Park, *et al.*, "Improved signal-to-noise ratio in spectral-domain compared with time-domain optical coherence tomography," Opt. Lett. **28**(21), 2067–2069 (2003).
5. M. A. Choma, M. V. Sarunic, and C. Yang, *et al.*, "Sensitivity advantage of swept source and Fourier domain optical coherence tomography," Opt. Express **11**(18), 2183–2189 (2003).
6. S. Azzollini, M. Monfort, and O. Thouvenin, *et al.*, "Dynamic optical coherence tomography for cell analysis [Invited]," Biomed. Opt. Express **14**(7), 3362–3379 (2023).
7. R. Morishita, T. Suzuki, and P. Mukherjee, *et al.*, "Label-free intratissue activity imaging of alveolar organoids with dynamic optical coherence tomography," Biomed. Opt. Express **14**(5), 2333–2351 (2023).
8. T. Monfort, S. Azzollini, and T. Ben Yacoub, *et al.*, "Interface self-referenced dynamic full-field optical coherence tomography," Biomed. Opt. Express **14**(7), 3491–3505 (2023).
9. Y. Hwang, S. Azzollini, and T. Ben Yacoub, *et al.*, "Retinal blood flow speed quantification at the capillary level using temporal autocorrelation fitting OCTA [Invited]," Biomed. Opt. Express **14**(6), 2658–2677 (2023).
10. Y. E. A. Moriguchi, "Extended and adjustable field-of-view of variable interscan time analysis by ammonite-scanning swept-source optical coherence tomography angiography," Biomed. Opt. Express **14**(8), 4112–4125 (2023).
11. J. Wang, T. T. Hormel, and S. T. Bailey, *et al.*, "Signal attenuation-compensated projection-resolved OCT angiography," Biomed. Opt. Express **14**(5), 2040–2054 (2023).
12. J. E. A. Liao, "A fast optical coherence tomography angiography image acquisition and reconstruction pipeline for skin application," Biomed. Opt. Express **14**(8), 3899–3913 (2023).
13. J.D. Li, C. Viehland, and A.-H. Dhalla, *et al.*, "Visualization of surgical maneuvers using intraoperative real-time volumetric optical coherence tomography," Biomed. Opt. Express **14**(7), 3798–3811 (2023).
14. R.M. Trout, C. Viehland, and J. D. Li, *et al.*, "Methods for real-time feature-guided image fusion of intrasurgical volumetric optical coherence tomography with digital microscopy," Biomed. Opt. Express **14**(7), 3308–3326 (2023).
15. A.A. Plekhanov, E. V. Gubarkova, and M. A. Sirotkina, *et al.*, "Compression OCT-elastography combined with speckle-contrast analysis as an approach to the morphological assessment of breast cancer tissue," Biomed. Opt. Express **14**(6), 3037–3056 (2023).
16. G. Regnault, M. A. Kirby, and R. K. Wang, *et al.*, "Possible depth-resolved reconstruction of shear moduli in the cornea following collagen crosslinking (CXL) with optical coherence tomography and elastography," Biomed. Opt. Express **14**(9), 5005–5021 (2023).
17. K. Metzner, Q. Fang, and R. W. Sanderson, *et al.*, "Analysis of friction in quantitative micro-elastography," Biomed. Opt. Express **14**(10), 5127–5147 (2021).
18. M.Q. Duan, R. A. Byers, and S. G. Danby, *et al.*, "Potential application of PS-OCT in the safety assessment of non-steroidal topical creams for atopic dermatitis treatment," Biomed. Opt. Express **14**(8), 4126–4136 (2023).
19. K. Li, B. Liu, and Z. Wang, *et al.*, "Quantitative characterization of zebrafish development based on multiple classifications using Mueller matrix OCT," Biomed. Opt. Express **14**(6), 2889–2904 (2023).

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20. S. Frisken, T. Anderson, and A. Segref, *et al.*, "Anterior and posterior imaging with hyperparallel OCT," Biomed. Opt. Express **14**(6), 2678–2688 (2023).
21. J.D. Malone, I. Hussain, and A.K. Bowden, "SmartOCT: smartphone-integrated optical coherence tomography," Biomed. Opt. Express **14**(7), 3138–3151 (2023).
22. K. Chen, W. Song, and K. Bizheva, *et al.*, "Powell lens-based line-field spectral domain optical coherence tomography system for cellular resolution imaging of biological tissue," Biomed. Opt. Express **14**(5), 2003–2014 (2023).
23. L., Han and K. Bizheva, "Correcting spatial-spectral crosstalk and chromatic aberrations in broadband line-scan spectral-domain OCT images," Biomed. Opt. Express **14**(7), 3344–3361 (2023).
24. W. Zheng, S. S. Kou, and C. J. R. Sheppard, *et al.*, "Advancing full-field metrology: rapid 3D imaging with geometric phase ferroelectric liquid crystal technology in full-field optical coherence microscopy," Biomed. Opt. Express **14**(7), 3433–3445 (2023).
25. S. Alhaddad, O. Thouvenin, and M. Boccara, *et al.*, "Comparative analysis of full-field OCT and optical transmission tomography," Biomed. Opt. Express **14**(9), 4845–4861 (2023).
26. R. Wu, S. Huang, and J. Zhong, *et al.*, "MAS-Net OCT: a deep-learning-based speckle-free multiple aperture synthetic optical coherence tomography," Biomed. Opt. Express **14**(6), 2591–2607 (2023).
27. M. Miażdżyk, A. Consejo, and D.R. Iskander, "OCT based corneal densitometry: the confounding effect of epithelial speckle," Biomed. Opt. Express **14**(8), 3871–3880 (2023).
28. D. G. Revin, R. A. Byers, and M. Q. Duan, *et al.*, "Visible-light optical coherence tomography platform for the characterization of the skin barrier," Biomed. Opt. Express **14**(8), 3914–3923 (2023).
29. J. de Wit, G.-O. Glentis, and J. Kalkman, "Computational 3D resolution enhancement for optical coherence tomography with a narrowband visible light source," Biomed. Opt. Express **14**(7), 3532–3554 (2023).
30. Y. Gan, X. Li, and Z. Dong, *et al.*, "Frequency-aware optical coherence tomography image super-resolution via conditional generative adversarial neural network," Biomed. Opt. Express **14**, 5148-5161 (2023).
31. T.M. Cannon, B.E. Bouma, and N. Uribe-Patarroyo, "Mapping optical scattering properties to physical particle information in singly and multiply scattering samples," Biomed. Opt. Express **14**(8), 4326–4348 (2023).
32. L. Zhu, S. Makita, and J. Tamaoki, *et al.*, "Multi-focus averaging for multiple scattering suppression in optical coherence tomography," Biomed. Opt. Express **14**(9), 4828–4844 (2023).
33. K. Tomita, S. Makita, and N. Fukutake, *et al.*, "Theoretical model for en face optical coherence tomography imaging and its application to volumetric differential contrast imaging," Biomed. Opt. Express **14**(7), 3100–3124 (2023).
34. H. Luo, S. Li, and S. Kou, *et al.*, "Enhanced 3D visualization of human fallopian tube morphology using a miniature optical coherence tomography catheter," Biomed. Opt. Express **14**(7), 3225–3233 (2023).
35. Y. Mellak, A. Achim, and A. Ward, *et al.*, "A machine learning framework for the quantification of experimental uveitis in murine OCT," Biomed. Opt. Express **14**(7), 3413–3432 (2023).
36. Y.A. Bayhaqi, A. Hamidi, and A. A. Navarini, *et al.*, "Real-time closed-loop tissue-specific laser osteotomy using deep-learning-assisted optical coherence tomography," Biomed. Opt. Express **14**(6), 2986–3002 (2023).
37. J. D. Farrell, J. Wang, and D. MacDougall, *et al.*, "Geometrically accurate real-time volumetric visualization of the middle ear using optical coherence tomography," Biomed. Opt. Express **14**(7), 3152–3171 (2023).
38. A. E. A. Rivail, "Deep survival modeling of longitudinal retinalOCT volumes for predicting the onset of atrophy in patients with intermediate AMD," Biomed. Opt. Express **14**(6), 2449–2464 (2023).
39. S. Hao, M.M. Amaral, and C. Zhou, "High dynamic range 3D motion tracking using circular scans with optical coherence tomography," Biomed. Opt. Express **14**(8), 3881–3898 (2023).
40. M.P. Urizar, E. Gambra, and A. de Castro, *et al.*, "Optical beam scanner with reconfigurable non-mechanical control of beam position, angle, and focus for low-cost whole-eye OCT imaging," Biomed. Opt. Express **14**(9), 4468–4484 (2023).
41. Á. Barroso, S. Ketelhut, and G. Nettels-Hackert, *et al.*, "Durable 3D murine ex vivo retina glaucoma models for optical coherence tomography," Biomed. Opt. Express **14**(9), 4421–4438 (2023).
42. H. Zhang, J. Yang, and C. Zheng, *et al.*, "Annotation-efficient learning for OCT segmentation," Biomed. Opt. Express **14**(7), 3294–3307 (2023).